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ABSTRACT

Two computer-based instructional projects and a workbook model designed to emphasize three different applications of expertise in medical problem-solving are described. The "CVTEST" Project (cardiovascular) explored the use of a computer program to provide guidance to students and facilitate self-assessment. The program does not directly teach, but provides support to students in the form of goals, content analyses, questions, and feedback discussions. The "Diagnostic Workbook" Project presents examples of expert problem-solving as illustrations of the process involved in the formation of a cognitive image of a case. Accompanying each case are the protocol generated during the simulation exercises by either an expert or novice subject, a critical annotation of the protocol, generated by the expert consultant, and exercises (along with correct answers). The decision support model was designed to provide decision support by giving information tailored to clinical tasks. Among principles listed for the formation of the system are that it would supplement meta-knowledge and that it extend domain knowledge. A sample of the "CVTEST" Project questions and workbook exercises and feedback are appended. (PHR)

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EDUCATIONAL APPLICATIONS OF A THEORY OF CLINICAL EXPERTISE[1]

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University of Minnesota

Johnson (1979) and Swanson (1979) have described theoretical and experimental investigations of the nature of expertise in solving problems in medicine by a group at the University of Minnesota. In addition, we have explored some ways in which our work can influence educational practice. This paper reports three such applications that have been created or are in progress.

1. THE "CVTEST" PROJECT

Context

The first project was an attempt to create an instructional device that could enhance learning in a medical school course covering the cardiovascular system. At the University of Minnesota this is taught, as are the other major organ systems, in an intensive six week course during the second year. This course introduces students to the function and diseases of the heart and blood vessels, and is the major exposure to this field for students who will not specialize in internal medicine, including thsoe who will become general practitioners. All (approximately 250) students are enrolled together in the course, which consists primarily of sixteen lectures by a total of ten faculty members. There are four optional small group case conferences (about twenty students each) and simultaneous clinical experiences in the hospital, although it has not been possible to arrange for students to be working with a patient suffering from diseases they are studying at the time. A two hour final exam is the only evaluation.

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[1]Paper presented at the annual meeting of the American Educational Research Association, San Francisco, 1979.

The assistance of Paul Johnson in the preparation of this paper is gratefully acknowledge.

Problem

Based on observations and interviews with students and faculty, a number of inadequacies in this situation were identified. First, in terms of content, most materials treat the various areas within cardiovascular medicine as if they were unrelated, and the number of lecturers aggravates this problem. Furthermore, there is little relation to the anatomy and physiology learned in the previous year's basic science courses, or to the tasks and operative knowledge of actual clinical work.

In terms of teaching strategy or method, there is no opportunity for systematic feedback other than the final examination, so students are given no indication of their progress or information that might guide their study. This problem is accentuated because students are not otherwise given a clear idea of what they are expected to accomplish. (A partial list of objectives is provided, but these neither represent competence in the field nor even provide criteria that will, if met, insure passing the course).

Constraints

The instructional intervention we could design to address these problems was limited because the project team was independent of the medical school (although one member was one of the faculty for the course) and no curriculum reform was mandated. Any materials would have to be supplementary to the course and had to be offered to all students on an optional basis, with it made clear that there was no direct intent of helping them meet their only concrete immediate requirement, passing the final examination.

Method

To supplement the cardiovascular course, a learning aid was created[2]

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[2]Stephen Greenfield, M.A., Thomas C. Gilmore, M.B.A. and James Moller, M.D., worked on this project, with assistance from Paul E. Johnson, Ph.D. and medical students David Dreis, Oliver Cass and Mark Jensen. The project was supported by a grant from the Univ. of Minnesota Center for Educational Development.

in the form of a computer program called CVTEST, to provide guidance to students and facilitate self-assessment. It does not directly teach, but rather provides support to students in the form of goals, content analyses, questions, and feedback discussions. Of familiar types of educational methods, it is most similar in format to computer-managed instruction. The program was designed to be content independent and run materials prepared for any of the major topics in the course.

The principles that guided design of this program, and its features, are described in detail elsewhere (Greenfield, 1977), but several will be explained here.

(1) What is expected of students is specified. This is done not only to help them study efficiently but also to influence their organization of knowledge and their thinking about the domain.

These expectations are expressed in the form of "cognitive objectives" (Greeno, 1976) based largely on the categories of knowledge and the problem-solving processes of our model. For example, one goal within the subtopic of valvular heart disease is to "figure out the consequences of a malfunctioning valve", which is further broken down to indicate the pathophysiological principles students should be able to apply and the categories of consequences they should be able to deduce (e.g., hemodynamic changes, secondary anatomic changes, clinical manifestations), and so forth. This is a category of domain knowledge and corresponds to the "expectations" that are embedded in Swanson's (1978) simulation. It is not an attempt to teach problem solving, but to influence students to think of domain knowledge in a proceduralized form that can be related to their hypothetico-deductive process base. Similarly, another goal seeks to facilitate the transfer of knowledge from this introductory course to later clinical problem-solving by requiring "bottom-up" reasoning. For example, in CHD, students are

expected to be able to explain the physiological cause and significance of common abnormal findings and name defects that can produce them. Other goals describe necessary system and feature knowledge, such as familiarity with cardiac anatomy, or understanding the mechanisms of electrocardiography. These goals and objectives were prepared in three levels of increasing detail, and in CVTEST students could review them in as much detail as desired at any time.

This analysis also determined the organization of the program, as subtopics were formulated and sets of questions were prepared and selected to correspond to those goals.

(2) Our model of knowledge contributed to the content of the specific objectives and of the questions and comments prepared for the program. Components covering domain knowledge were stated in a way that can be related to hypothetico-deductive thinking, as suggested above. Heuristics present in the model and employed by expert diagnosticians were used in creating materials. For example, students are pushed to think of diseases in multiple hierarchical frameworks, such as a classification of types of anatomical defect, or categories of clinical characteristics. In addition, a number of conceptual organizers that are useful as learning aids, such as the Wigger's (simultaneous pressure) diagram, are features. These indirectly help students achieve increasing competence by structuring their knoweldge and experience in effective ways.

(3) A large body of questions for self-assessment was prepared, based upon the analysis and organization described above.[3] Three levels of feedback were provided. First, responses that are incorrect (or were correct but given with a low confidence rating) are followed by comments intended to correct errors of domain knowledge. Second, when students complete a subtopic their performance

[3]The prototype version required questions to be in multiple choice format, but this was later extended to handle verbal or mathematical short answers without special coding. In year 2 a confidence rating was required with each answer and was used to modify the scoring.

is assessed and suggestions for additional work are given. The program monitors performance on a subtopic and may suggest they leave early if an assessment can be made. In the final level of feedback, the whole pattern of a learner's responses is surveyed to infer weaknesses that may appear across items. This is done by setting a code for each item that indicates the knowledge it taps on a number of dimensions. The dimensions were selected to fit with our model of knowledge of heart defects: for example, the type of reasoning required, the category of disease concerned, and the clinical tools involved. Thus a student may have made errors on questions in a number of subtopics that indicate an inadequate knowledge of X-ray findings, or of obstructive defects, and a brief explanation and description, including suggested references, would be given.

(4) Learners have control over what parts of the material in CVTEST they want to examine and work on. At the same time, the program is adaptive in that it uses on-task performance to determine the number of questions to be done on a subtopic, and to diagnose what knowledge is inadequate, using the mechanisms described above. However, there are presented as suggestions and can be ignored. For example, a student whose performance on questions in a subtopic is persistently high will be urged to proceed to another area, but he does have the option of continuing if that meets his needs.

(5) Although it is not the major issue in this paper, it should be noted that CVTEST was designed to <u>supplement</u>, and offset observed weaknesses within a course, rather than <u>replace</u> the existing teaching method. As Rothkopf (1973) has argued, the latter strategy has been unproductive because it attributes too much importance to the materials, rather than to the active role of the learners themselves. As he suggests, it may be more effective to design "learning aids" to help students make optimal use of existing resources than to give a different set of materials and methods.

Use of the Program

A brief scenario of student usage will make these features more understandable. The student signs on and is given an introduction if it is the first contact or if a reminder is desired. The student is shown the subtopics for the topic CVTEST is presently running, and goals and expectations for each can be examined. When a subtopic is chosen, the program presents questions, and the student must respond and rate confidence in each answer, after which feedback is given as needed. The student can continue on that subtopic, or switch to another, or reexamine the goals and objectives. Depending on performance, the program may interrupt to propose that the student should stop working on the subtopic, and when he does so more feedback and suggestions for remedial or further study are given. When the student has worked on all parts of the course, or otherwise wants to quit, the program analyzes the total pattern of responses and gives further feedback, advice, and references.

This scenario is similar to what might take place on other computer-based self-evaluation systems that have been created by several larger projects at other universities (Jones and Sorlie, 1976; Nishimoto and Walters, 1972). The present approach is distinguished primarily by the strong attention, with theoretical underpinnings, to the content analysis, and the emphasis on thorough feedback.

Results

A prototype of CVTEST covering one of the major course topics, congenital heart disease (CHD), was offered to students in the 1976-1977 class ("year 1"). About one-third of the class (80 out of 250 students) used the program, with average total time approximately 55 minutes. A number of other students reported that they had wanted to participate but were prevented by the limited number of

suitable terminals available and convenient to the medical school (two CRTs and two high-speed printers).

Examination of usage data recorded on the system showed great variation in the relative amounts of time students spent on the four sections of the program (data on the sequence they selected was not stored). This suggests that students did take advantage of the possibilities for learner control.

The patterns of incorrect answers to CVTEST questions varied greatly, so the program had to deliver feedback and prescription messages that were unique (in effect highly individualized). Item difficulties were estimated by average score for all users who attempted each question[4], and the overall mean was 64%, which is a fairly good level of difficulty for providing informative feedback. An item analysis would have been inappropriate, but questions with extremely high or low difficulty were scrutinized by subject matter specialists. Several of these were seen as confusing and dropped or revised, but since this program was not intended as an evaluation instrument, others were felt to be instruction and were retained.

User opinions were collected with questionnaires to supplement the formative evaluation (see Discussion). The possibilities for doing an experimental test were severely constrained because users and non-users could not be selected randomly, and background information on students was not released. Alternative programs omitting particular features could not be given to control groups, and no special assessment device to test critical outcomes relating to clinical thinking could be administered to all the students.

The only dependent variable readily available was course final examination score, but since random assignment and other controls were not permitted,

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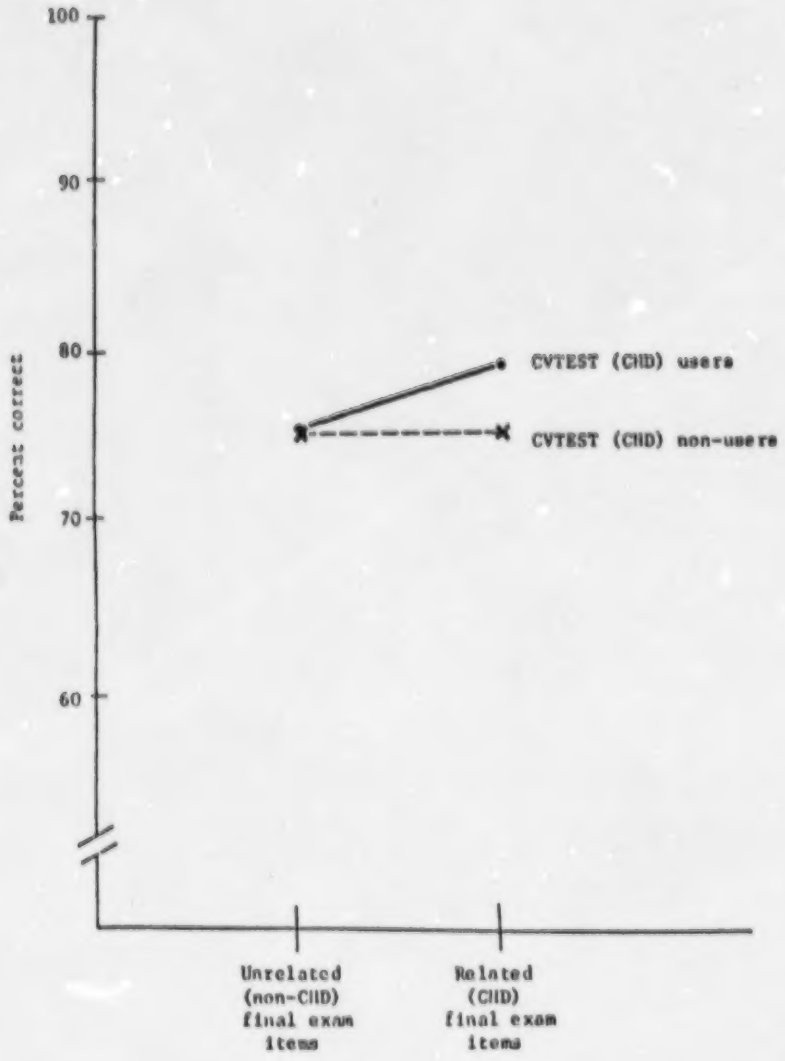
[4]This score included partial credit for certain responses (and the year version added a weight for confidence of the answer) so it does not provide a true difficulty value.

comparison of the scores of program users and non-users would be hopelessly confounded by self-selection and "Hawthorne" effects. To overcome this, the dependent variable of score on only those final exam items related to the topic addressed by the program, congenital heart disease (CHD), was compared to scores on other (non-CHD) questions, for both the students that used CVTEST (user group) and those that did non (non-users).

Exam results showed that users had slightly higher scores on the CHD items than did non-users (79.8% vs. 75.4%, $t\ (171.36) = 2.64$, $p < 0.01$), although there was no difference in non-CHD score between the groups (75.3% and 75.7%, respectively; $t(236) = .036$, $p = .717$). This is shown graphically in Figure 1. A more careful test of this comparison, taking our variation in non-CHD score as a covariate, reaffirmed a significant effect of CVTEST usage on CHD score ($F_{(1,235)} = 5.7$, $p < .02$).

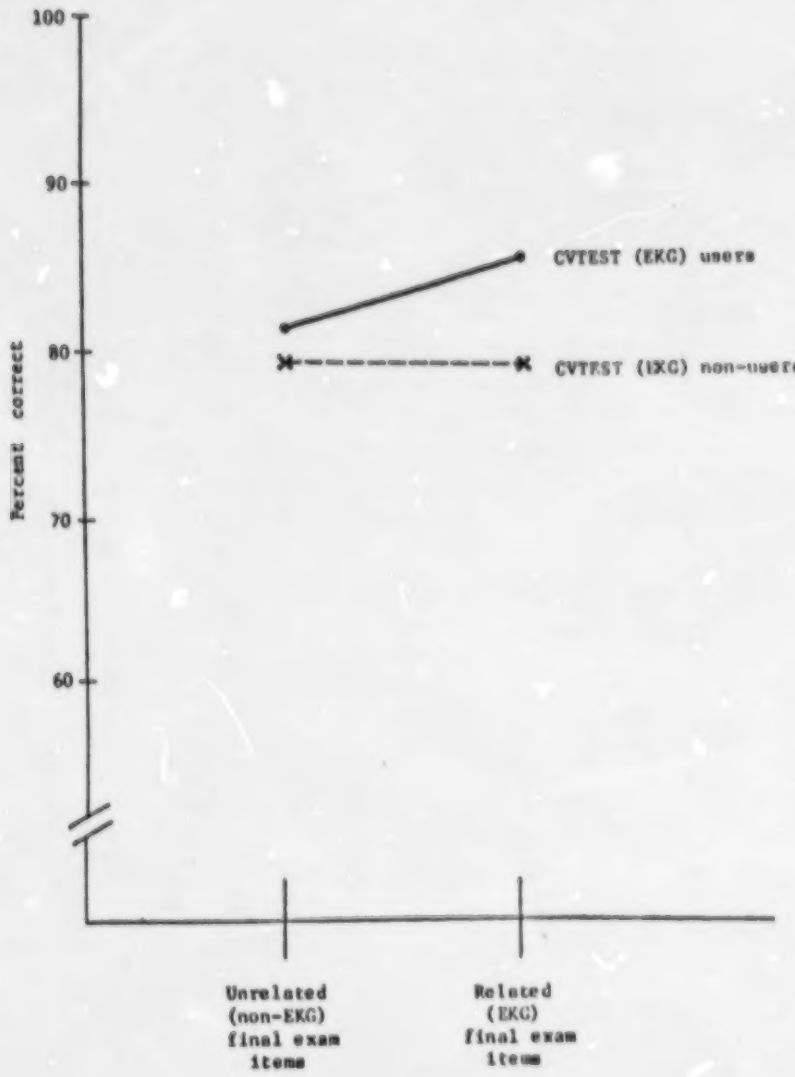
Following the year 1 course, CVTEST was modified and extended to two additional content area, valvular heart disease (VHD) and electrocardiography (EKG). The three versions of the program were used in the 1977-1978 course (year 2) by 49, 56, and 122 students, respectively, out of a class of 240.

Final exam scores in year 2 replicated the initial results. The students who used CVTEST for each of the three topics scored 4-5 percentage points higher on related final exam items than students who did not. The results on the use of the program for electrocardiography (EKG) were most similar to the year 1 results, with use of the program linked to improvement in related items only, since non-users did no better on EKG items than on non EKG items (See Figure 2). The treatment effect was again significant when score on unrelated (here, non-EKG) items was taken as a covariate ($F_{(1,185)} = 7.8$, $P < .01$). On the other two topics (congenital-CHD - and valvular heart disease - VHD), however, users of the corresponding CVTEST material scored better on <u>both</u>



YEAR 1 FINAL EXAMINATION RESULTS

Figure 1.



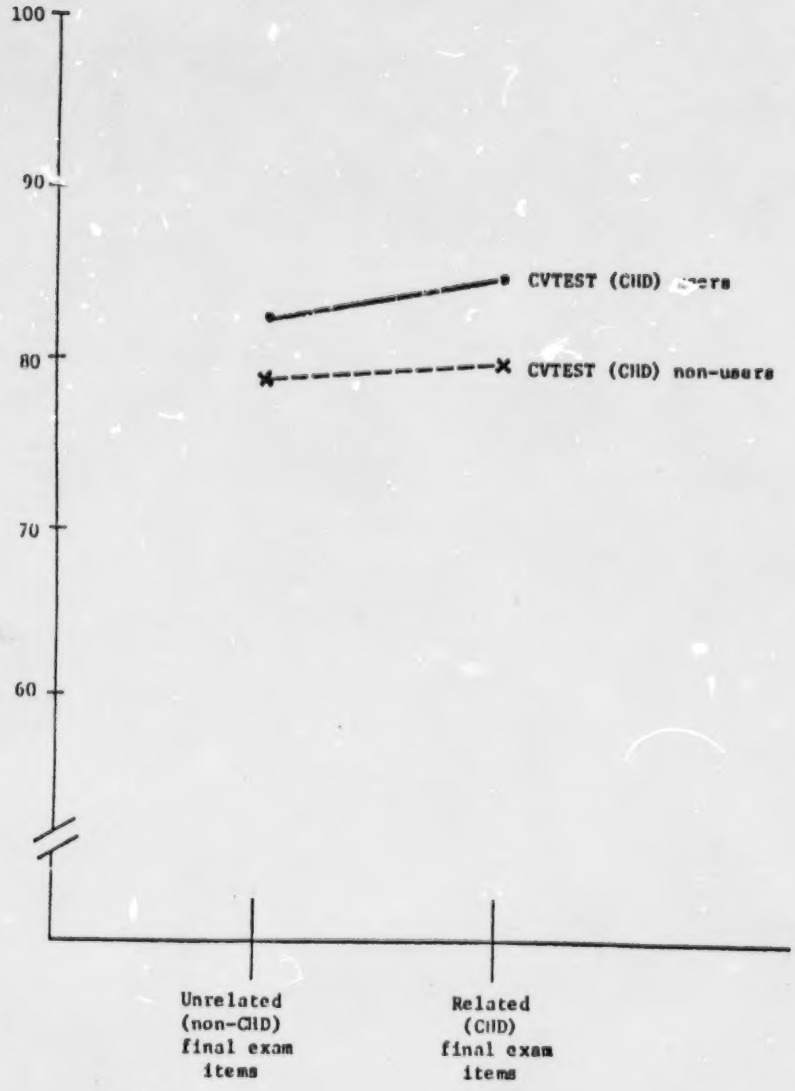
YEAR 2 FINAL EXAMINATION RESULTS

Figure 2.

related and unrelated items (see Figure 3), so the analysis of covariance showed no differential effect on relevant items (F = 0.26, p = 0.74, respectively). To interpret this result, we obtained further information on the students. Comparison of undergraduate science grades and MCAT scores (analysis of variance of the values, and a Kruskal-Wallis test on their rankings) showed no ability differences between users and non-users of any of the CVTEST topics. This suggests that the use of CVTEST on those two topics had a general positive effect, rather than the alternative explanation - that the users were superior students and therefore that the program had no effect. In terms of the subject matter, it is reasonable to suppose that material on congenital and valvular heart disease, which includes pathophysiological principles (part of the system knowledge) common to other aspects of heart function and disease, would allow more transfer than that covering electrocardiography, which contains unique feature knowledge that has little direct relation to other clinical tools.

DISCUSSION

Additional qualitative information was gathered to interpret the effectiveness of the program. First, we needed to determine, particularly in the formative evaluation of the year 1 prototype, satisfaction with the program. An aid, however effective, is not valuable if it is not in a form that will be used. A short on-line questionnaire yielded uniformly positive reactions (appendix A). Students felt the program was very helpful and overwhelmingly stated that they would be interested in using such a system for other topics (mean response 4.79 on a 1-5 scale). Opinions were also positive in year 2, although not as strongly as the first year. A questionnaire item added in year 2 showed considerable agreement that "terminal and program problems reduced the effectiveness of the course" (mean, for all topics, 3.6 on the 1-5 scale), which probably contributed to the drop in acceptance.


100
90
80
70
60
CVTEST (CHD) users
CVTEST (CHD) non-users
Unrelated (non-CHD) final exam items
Related (CHD) final exam items
YEAR 2 FINAL EXAMINATION RESULTS

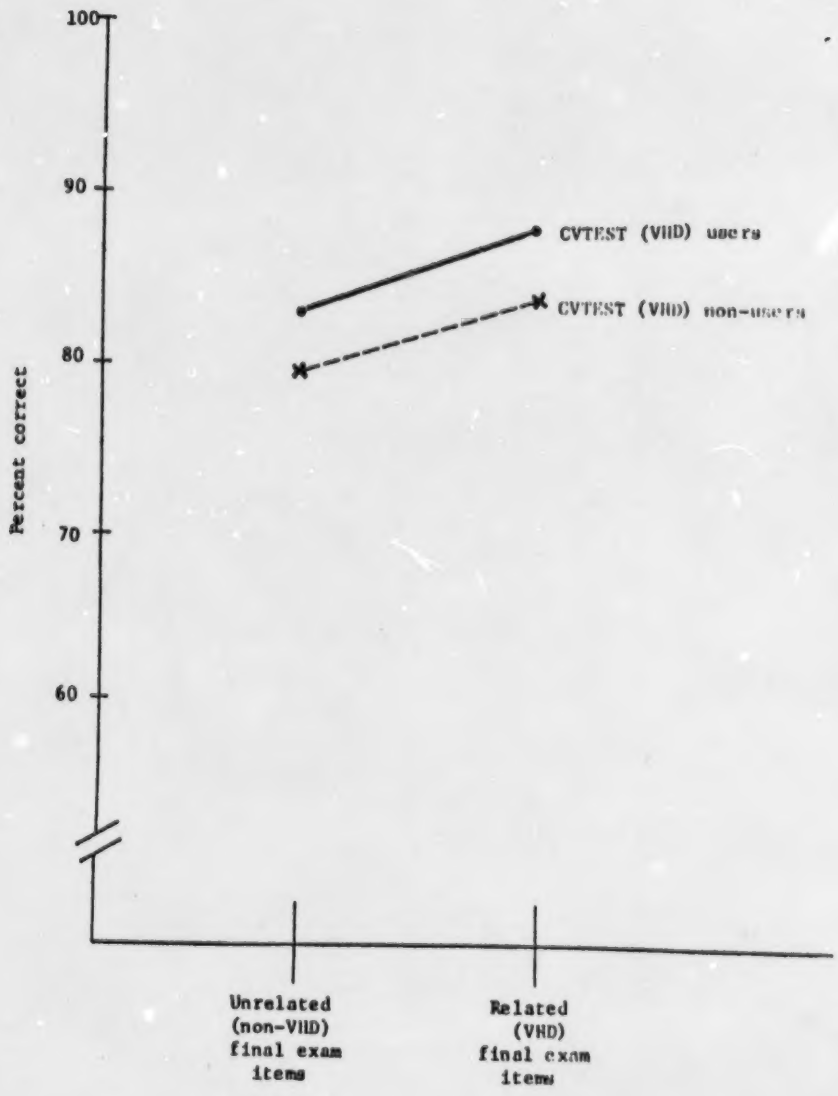

100
90
80
70
60
Percent correct
CVTEST (VHD) users
CVTEST (VHD) non-users
Unrelated (non-VHD) final exam items
Related (VHD) final exam items
YEAR 2 FINAL EXAMINATION RESULTS

Figure 3.

Other items on the on-line questionnaire were designed to assess the suitability of certain features of the system. Since the intent was to maximize informative feedback, it was important that questions were not perceived as too difficult or too easy. Students rated the difficulty of the questions at about the middle of the scale (mean 3.23 on a 1-5 scale), which seems optimal.

Students planned to make moderate use of the suggested references (item 118), and did not find the presentation of objectives very useful (item 120). These items raised doubts that students were just employing the program to practice answering questions, so a series of questions were posed on a follow-up questionnaire at the end of the course to investigate this. Only 21% of the users stated that they used CVTEST for test practice only, while 48% said it had a slight effect on how they studied the congenital heart disease topic, and 31% said that effect was considerable, so it apparently was used for self-assessment and guidance as we had hoped.

An additional item on the year 2 questionnaire further probed the role of the program. Students agreed that "the questions will help me apply course content in clinical settings" (means 4.3, 3.7 and 3.8 on 1-5 scales), which was an important indirect purpose of the project.

The questionnaires were limited in length to increase the probability of (voluntary) completion. Follow-up interviews with a sample of twelve users sought to clarify some problems. It appeared that apparent dissatisfaction with the objectives had been found because the question (item 118) did not distinguish those students who took the option of skipping detailed analysis of goals from those who examined them and had criticisms. No students expressed complaints about the actual form of the objectives.

Students had a wide range of opinions on the faults and merits of the program, and on the nature of an ideal system. Most desired material of a more

clinical nature, a complaint they apply to many aspects of their courses. Minor errors were felt to be seriously annoying, and most of the students were computer-naive and did not really distinguish between computer and terminal problems, program bugs, and controversial content. Finally, opinions were equally divided on whether using the program increased or reduced the time spent studying the corresponding topic area.

Conclusion

The CVTEST program met our primary goal of providing an aid to students that would increase their learning in a medical school course. Though constraints made it impossible to separate the effects of various design features, the framework of expert operative knowledge proved to be helpful in solving a practical educational problem by providing a basis for content analysis and for the structure of the program. In brief, CVTEST was designed to influence beginning medical students to acquire and organize system, feature, and domain knowledge in ways that are conducive to using them in applied, clinical thinking. A real test of this goal will not be made until we can design and administer a valid measure of clinical problem-solving.

To contribute more clinical thinking, particularly after these initial levels of training, attention must be paid to developing planning knowledge and to formation of a cognitive image, and more direct contact with the contextual and case-specific nature of medical expertise. The next part of this paper describes such an application that is being developed by A.J. Josefowitz and Dr. J.H. Moller.

2. THE "DIAGNOSIS WORKBOOK" PROJECT

Introduction

The purpose of this section is to describe a workbook[5] designed to illustrate

[5]This work was supported by a grant from the University of Minnesota Center for Educational Development.

and annotate aspects of medical diagnosis in the domain of congenital heart disease in an effort to train and sharpen skills of clinical thinking. A major objective of the workbook is to focus on the teaching of planning knowledge and meta-knowledge, as described in a previous paper (Johnson, 1979), for medical diagnosis. That is, rather than expand upon existing domain knowledge, the workbook is intended to direct what the user already knows toward more efficient and thorough diagnostic skills.

Compared to domain knowledge, planning and meta knowledge aspects of diagnostic skills are much more difficult to teach. While knowledge of physiology, anatomy and other biological science areas is readily available through textbooks and lectures, clinical skills are embedded in the task of diagnosis itself. The most common approach to training in this area is the physician-medical student interaction of clinical rounds. Unfortunately, the constraints of the setting, as well as the physician-student ratio, hinder the acquisition of the more subtle skills of diagnostic thinking. That is, while the physician may be demonstrating clinical skills, given that the skills are embedded in the task and have reached advanced stages of automaticity, and given the demands upon the medical student, these skills may go undetected. Furthermore, the student's experience will be determined by the cases that happen to be in evidence when they are on rounds.

We address these issues by giving students annotated records of physicians' clinical thinking followed by opportunities to analyze those records and to engage in clinical problem-solving themselves. The workbook incorporates examples of diagnostic reasoning from several physicians for each case presented to point out varying styles of clinical reasoning. It then provides the additional feature of annotation by an expert, so that the user not only witnesses certain skills but also can understand their motivation and appreciate their

value (efficient and thoroughness) in the context of the case. In fact, the workbook strives to present examples of both "good" and "bad" clinical reasoning, and the annotations highlight the strengths and weaknesses of each. The workbook, then, not only presents exemplars of good diagnostic skills but also illustrates common mistakes that non-experts commit.

User exercises are incorporated into the workbook to promote learning and increase user involvement in the diagnostic skills being discussed. Exercise questions ask the user to select data, generate and test hypotheses, and critically assess the diagnostic protocol.

DESCRIPTION

The nucleus of the workbook is protocol data collected form physicians performing tasks of simulated diagnosis (Mandernach, 1979). Participating physicians were classified into one of two categories: expert or novice. Experts are physicians in the specialty area of pediatric cardiology with numerous years of diagnostic experience, while novices are medical students near completion of their undergraduate medical school training. The cases chosen for the workbook have been classified into two categories: moderate and difficult. Moderate cases were distinguished on the basis of infrequency of the defect (e.g., truncus arteriosus, tricuspid atresia, etc.). Difficult cases were distinguished as being enigmatic and having presented difficulties to experts.

The workbook presents several expert and novice protocols for each patient case. Cases were sampled from those used in an original study of clinical reasoning (Mandernach, 1979) and were chosen by a physician consultant on the basis of the instructive nature of the workup done by the physician in the simulation study. The selection process was motivated by the desire to have the workbook illustrate both good and bad approaches to clinical problem-solving across cases with both disease and difficulty differences.

Cases consisted of patient chart data and accompanying EKG tracings and

X-ray photographs. Accompanying each case were (1) protocol generated during the simulation exercises by either an expert or novice subject, (2) critical annotation of the protocol, generated by the expert consultant, and (3) exercises, along with correct answers.

The exercises were constructed to reflect key diagnostic skills within the protocols. Exercises concerned with specific skills or problems are interspersed within the case protocols, while more general exhaustive exercises appear at the end of each case. The exercises ask the user to participate in the diagnosis by making decisions on data acquisition and interpretation and hypothesis formation, and critically evaluate those strategies demonstrated in the protocol. Exercises also permit users to offer subjective opinions about the status of certain data (i.e., their diagnostic implications), hypotheses entertained in light of data collected, and strategies of clinical reasoning (See Appendix B).

Answers to these exercises, as generated by the consultant, are provided at the end of each case study so that the user may check his work.

Also included in the workbook are an introduction to workbook use and design, and an overview of the nature of medical diagnosis from a physician's persepctive. These sections serve to detail the objectives and proper use of the book.

Nature of Annotation

In critiquing the protocols, the expert was able to identify features in the diagnostic behavior of his colleagues that are consistent with elements of our theory.

(1) Hypothesis Generation: A general conclusion to be drawn from research in medical problem solving is that hypothesis generation (part of what we have termed the process base) is central to the task of clinical diagnosis (Elstein, et al, 1978). Once a hypothesis or multiple hypotheses are generated, these

activated hypotheses then influence the nature and sequence of further data collection. The annotation points out and discusses which hypotheses are being considered and critiques the subsequent diagnostic approach, given the stated hypotheses.

Figure 5 is an excerpted piece of a case study from the workbook. The main text is a physician generated piece of protocol while the boxed protocol on the margins are critical annotations thereof, addressing issues of data collection and hypothesis generation and of patient model construction. The annotations are both descriptive and critical in nature. The critical annotations (on the right side) assess procedures, judgments, and hypotheses generated by the physician in light of the case-specific information.

(2) Cognitive image: Throughout the course of diagnosis, the physician constructs a patient model that is his cognitive image of the case. In straightforward cases, these mirror theoretical models of the disease. In many cases, however, complications (such as multiple disorders) cause the developing patient model to differ from the theoretical textbook model. The annotation points out the physician's image of the case and shows how it is constructed and how it influences his thinking and strategies. In Figure 6 the right margined annotation addresses the physician's image or model of the case and discusses its appropriateness given the specifics of the case.

(3) Domain knowledge: Though it was not our intent to systematically present subject-matter information, the expert often points out missing pieces of critical domain knowledge, such as triggers and disconfirmation evidence. These are rarely unknown to the physicians and users, but are just not recalled to working memory when needed. Thus the workbook provides experience in the application of domain knowledge to clinical problems.

(4) Meta-knowledge: The expert is periodically able to point out where the

It sounds like a history that I've had periodic episodes of congestive heart failure at least presumptively so on the basis of being on anticongestive measures.

Until this point, information has been gathered to make these diagnostic options.
Hypothesis: 1. VSD
2. Admixture lesions
3. Shunt lesion

Confirms the presence of CHF. States murmurs are not specific, but later affixes them to the diagnosis of VSD, etc.

Um, murmurs are not particularly suggestive of any one particular lesion except maybe a shunt lesion, a VSD or possibly an admixture lesion.

Too vague a classification of hypothesis--too general, i.e. shunt lesion, admixture lesion; if he were more specific he would have to review the finding

I'm a little bit perplexed about the description of the cyanosis whether or not the fact that that is real or apparent or not, I think I just have a subjective feeling about it at this point it might be present.

Pursuing cyanosis for this is important in knowing if an admixture lesion is present.

But whether or not I'm dealing with cyanotic or acyanotic congenital heart disease is difficult for me to say.

Cyanosis--presence or absence is very important to making a differential diagnosis.

Figure 5

(Would there be something we could, any information that I could give you to help you on that?)

Well, I think maybe a little bit more historically in respect to whether this, what I'm visualizing in this particular time, is the same color that the mother visualizes; whether it changes in respect to activity, crying, stress, and so on so forth, so we may go back to get a little bit more history on that.

The examiner realizes cyanosis is a major feature and is trying to determine if it is present.

(I'm not sure that the mother would say that it has always been exactly the same as what you see right now, but we can presume that it would be, the mother having complained about color not being right).

If the physician had not been so concerned about presence or absence of cyanosis, but had concentrated on the other physical findings, he would have come closer to the diagnosis and without such effort, because the findings of S_2 and type of murmur indicate a shunt at atrial level.

Figure 6

diagnosticians got into trouble because of a poor awareness of their own skills and weaknesses. This can help illustrate the importance of meta-knowledge in clinical problem-solving, which can then be built up through exercises in diagnosis and comparison to the protocols presented.

Workbook Usage

The construction of the workbook in levels of information (see Figure 7) is intended to facilitate usage by individuals at varying levels of training. While more sophisticated users might be exclusively interested in the critical annotations accompanying a study, and then only some of them, the medical student might have interest in studying a case's development from its very outset (patient file data - level I) to its conclusion, and doing all the exercises.

The workbook design is not limited in scope in that cases can be worked up and added at any time. Synthetic cases could be developed to highlight specific aspects of clinical reasoning, both correct and common weak approaches. Cases that point out specific features that lead to common errors of clinical reasoning would be particularly useful. Such work has already been initiated (Feltovich, 1979).

Summary

This section has described a workbook, still in early stages of development, that is designed to improve the clinical skills of advanced learners by illustrating and discussing examples of expert problem-solving. The intent is not to increase domain knowledge, but to help the user sharpen planning knowledge, the process base, and the formation of a cognitive image of the case through the multi-levelled analysis of particular cases. It is in the use of several diagnostic protocols, and in particular the commentary on the case and on those protocols by an expert in the field, that this workbook differs from "patient management problems" (McGuire and Solomon, 1971) and other case-based instructional materials.

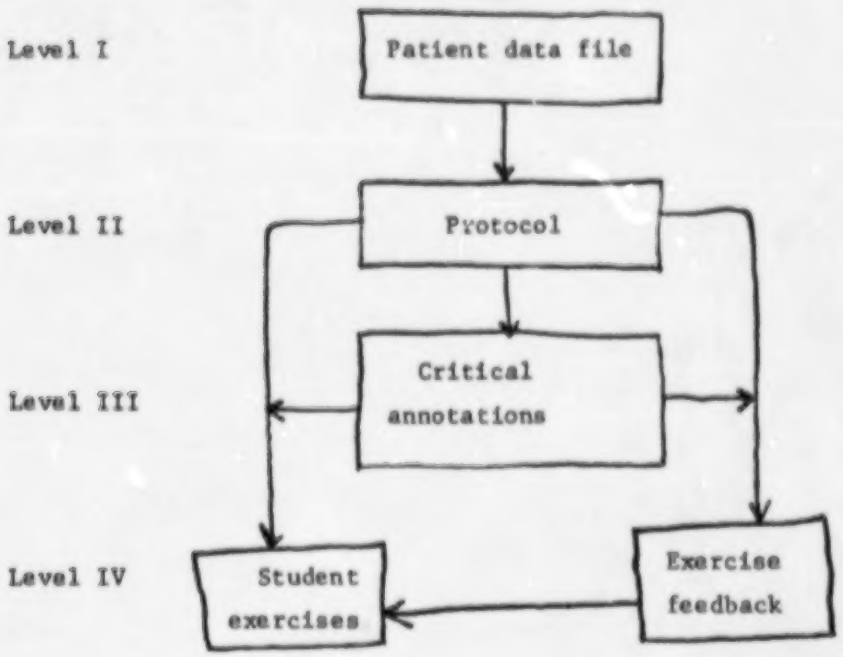


Figure 7.

Construction of workbook cases.

Like CVTEST, this workbook is a basically traditional application in that it is intended to increase expertise through education, that is training more experts. Training at this level will probably always require considerable time and resources, and may no longer be adequate to meet society's increasing need for expertise in medicine and other fields. Another traditional solution to this problem, increasing specialization, has limitations also.

One alternative may be to transfer expertise directly to those who need it without teaching per se, but in the mode of a "decision support system." The last part of this paper illustrates this by describing an attempt by members of our group to apply our model of expertise to the design of a system to support clinical problem solving by medical practitioners.

3. DECISION SUPPORT

The explosion of information in medicine is well known (Gabrieli, 1976) as are physician's limitations in coping with it (Christensen, 1974; McDonald, 1977). Practicing physicians try to meet their need for specific, decision-oriented information with a network of textbooks, journals, colleagues and consultants. The success of numerous attempts to provide them with effective computer support has been disappointing. Despite a documented ability to store and provide inforamtion relevant to medical decisions, computer-based information resources are not widely used and have little impact upon the practice of the busy primary care physician (Feinstein, 1974).

The major reason, we believe, for this state of affairs is that decision support systems in medicine have not been developed with an appropriate set of design objectives in mind, and, indeed, no established body of design principles is available.

Current approaches to computer-based decision support systems generally

focus on either diagnosis or the development of a comprehensive medical information system. The former approach is represented by statistical systems (typically Bayesian), and knowledge-based (artificial intelligence) systems. Their selective focus on diagnostic reasoning has restricted their applicability to patient management. Their theoretical foundations for decision-making are unfamiliar to the practitioner and frequently uncoordinated with his process of thought. The latter approach, medical information systems, often includes components for physician education as well as decision support, along with medical records, scheduling, billing. etc. However, this total systems approach requires major changes in existing medical practices and creates a significant hurdle to implementation. It is not coordinated with physician reasoning either.

Psychological analysis of clinical expertise suggests an alternative approach to designing a general purpose system. The medical expert's knowledge and skill are highly adapted to the tasks of diagnosis and management in the context of the clinical environment. This knowledge and skill is an untapped resource for systematic identification of practitioner's weaknesses and for the specification of the support that could be provided. A psychological understanding of clinical expertise clarifies the nature of the expert's adaptation and a methodology for collecting and representing that information.

The model developed in our research on expertise is one such source of principles for the design of decision support. To make these principles clearer, the model will be briefly reviewed. There are four major components of decision-making:

> The executive, a goal-directed agent (or control process) which selects information from a knowledge base, and data from the task environment, to guide the decision process.
>
> The cognitive image, an abstraction which is the executive's conscious perception of the decision task. This image is held in working (short term) memory and consists of task data, active hypotheses, and current "facts" about the problem.

The knowledge base, an organized aggregate of information stored in long term memory and referenced by the executive during decision making.

The process base, a collection of generalized procedures used by the executive to generation alternative hypotheses about the task and to evaluate these possibilities during decision making.

It is important to remember that, as Johnson (1979) and Swanson (1979) have described, experts and non-experts share this cognitive model.

There are two important guidelines we propose for the construction of a useful, effective computer-based decision support system in light of a model of expertise. First, decision support systems will be most successful if they provide assistance compatible with the process and architecture of the model. Second, a decision support system can provide valuable assistance by enhancing the capacity, performance, or reliability of any one of the model's components. When associated with a particular model, this leads to a set of specific principles for the design of a prototype system.

Principle #1: Structure and focus of cognitive image - Expert-based strategies for structuring and focussing the cognitive image take two forms: (1) strategies for generating and pruning lists of diagnoses and (2) strategies for grouping and organizing signs, symptoms, and laboratory data. These strategies are described below.

First, rather than actively considering all disease prototypes as possibilities until some are contra-indicated, a support system should encourage the user to not hypothesize specific prototypes until sufficient evidence suggests them. In practice an expert cardiologist does not generate an exhaustive differential diagnosis given an isolated elevated blood pressure, although if such a list were requested, it could be readily provided. The system should give the user a set of highly probable signs or symptoms for each prototype and encourage him to use these findings as "triggers" for activating diseases as a

cause for hypertension.

Second, when a set of triggers generates a number of hypotheses in the novice, the support system should provide a fairly rich store of information about the relative frequency of prototypes. The user can utilize this likelihood information to order active hypotheses, sometimes even eliminating those which are highly improbable from active consideration.

Third, when the user has utilized the available triggering and frequency devices to limit the number of active hypotheses, he can often distinguish among them by using a differential test in which findings are disparate for the prototypes. For example, evidence of previous streptococcal infection, such as a positive throat culture or an elevated ASO titer, distinguishes post-streptococcal glomerulonephritis from other renal disorders which cause hypertension. Such differential tests may be simply recalled directly or obtained from domain knowledge provided by the system.

Fourth, the support system can provide the user with knowledge of the invariant expectations for prototypes. These consequences of a prototype are expected with probability near one, and their presence or absence, therefore, can be used heuristically for diagnostic inclusion or rejection. For example, the finding of a significant blood pressure gradient between upper and lower extremities in a hypertensive child is coarctation of the aorta until proven otherwise.

The second strategic approach employed by experts to focus the cognitive image aims at grouping and organizing information. Different "levels" of hypotheses are used at different points in the decision process; for example, one might make an intermediate level hypothesis like left-to-right side communication and only later form a specific disease hypothesis. This avoids premature conclusions and also keeps the number of hypotheses small. Hypotheses can

be grouped together on the basis of similarities at differing levels of structural description. For example, in congenital heart disease all patients can be arbitrarily classified as either cyanotic or acyanotic. All cyanotic patients can be further subdivided by estimating their pulmonary blood flow from their chest X-ray. Thereby, one arrives at two or three most likely cardiac defects with only two pieces of information.

An expert-based decision support system can help the user to think of a disease grouping as a single entity. A disease group can be triggered, two groups can be discriminated with a differential test, or a disease group can be rejected. Appropriate use of grouping enables the novice to avoid processing on specific diseases until that is appropriate.

Principle #2 - Supplement meta-knowledge - Both medical expert and generalist share the ability to monitor their problem-solving activity based upon their awareness of strategies for success, their own fallibility as information processors, and specific and likely sources of error in particular problem-solving situations. Due to his greater experience, the expert has a relatively sophisticated set of such "rules of thumb" for achieving success and avoiding failure. Providing these to the user through the medium of a support system allows him to "mimic" the expert's efficiency and, depending upon the situation, match his success. For example, someone with greater experience would know that the most frequent cause of "hypertension" in hospitalized children is simply use of an inappropriate cuff size. Awareness of this common source of error in diagnosing pediatric hypertension could prevent an expensive, unnecessary workup.

In addition, the body of information and guidelines allows the physicians to conveniently make more careful checks of theis own accuracy.

Principle #3 - Provide planning knowledge - An understanding of expertise

permits creation of an explicit planning structure that shows the user how to think about his problem from beginning to end, from diagnosis through management. Such a structure prompts the user to consider issues that the expert "knows" are important and helps the user avoid premature conclusions and biased interpretations.

Flow charts are a familiar representation of planning knowledge. We use them here to map out possible sequences in the diagnosis and management of a patient with a given presenitng complaint or problem. These diagrams are developed by a staff of consulting medical experts, and serve to highlight key decision points. The frequent use of flow charts or "flow diagrams" in the Family Practice literature (e.g., Andrews, 1974) suggests their utility for providing organization for medical procedures.

Principle #4 - Extend domain knowledge - The expert has a large store of facts, principles, and prototypes that bear upon a user's problem. But more than this, he has organized his memory so that this knowledge is keyed to sequences of steps for solving specific problems. Making this knowledge available to the user reduces his reliance upon a fallible long-term memory, extends the range of prototypes he can consider, and, when necessary, enables him to build an appropriate system image for his problem.

This kind of information must be offered at points when it is needed, and should be hierarchical to provide rapid accessibility to key information and greater detail when desired. The structure should also allow revision of information to remain current with the rapid changes and expansion of medical knowledge.

Principle #5 - Simplify hypothesis evaluation and decisions - Human decision makers are most comfortable with relatively simple decision methods (e.g., Kahneman and Tversky, 1972). The expert simplifies the process of

reaching a good diagnostic conclusion in two basic ways: (1) he adopts relatively simple decision rules (e.g., disease features matched minus those not matched - see Swanson, 1978, Barrows et. al., 1978); and (2) he maximizes the effectiveness of simple rules by reducing variation in the clinical expectations for disease prototypes. This is done by factoring a disease into a number of discrete categories. Diseases such as ventricular septal defect (VSD) are subdivided into different sized defects at different ages, and the expert physician can then think about the clinical expectations of, say, a moderate-sized VSD in a six week old child." Even though data expectations in the patient are generally variable in a particular disease, when the disease is specified to a particular morphological variant, severity, and age, such effects become less variable, and many become nearly invariant.

Similarly, one reduces the variability in management of hypertensive patients by grouping them according to age and severity of blood pressure. For example, patients aged 7 to 12 with diastolic blood pressures of 90 to 100 mm Hg are initially managed with thiazide diuretics.

The above five principles are generated by focussing upon the cognitive framework for decision-making and expert/non-expert differences and commonalities. Such principles provide strategies for presenting information for decision-making, they do not specify exactly what kind of information should be presented, which will vary from situation to situation. An example is provided in the next section.

MEDINFO: A decision support system in medicine

MEDINFO, a system under development at the University of Minnesota[6], is

[6]Paul Johnson, Ph.D., George Biltz, M.D., Michael Prietula, M.S., Stephen Greenfield, M.A., Dennis Severance, Ph.D., and James Moller, M.D. have participated in this project. A prototype was developed on Control Data's PLATO system. a videotape of a user interacting with this prototype was prepared and can be provided by the authors.

designed to provide a primary-care physician with expertise in the form of information specifically tailored to meet the needs of his decision-making tasks. The purpose of this system is to improve the utility of medical information, to provide access to continuing education within the context of medical practice, and to reduce the cost of health care services by minimizing unnecessary referrals and inappropriate laboratory studies.

The base of expert knowledge is established by (1) identifying information and procedures used by experts in the medical specialties and subspecialties to make diagnostic and management decisions in specific and prototypical patient cases and (2) organizing this information for delivery to the primary-care physician so that it is relevant to his tasks, available when he needs it, at an appropriate level of specificity for his habits of thought, and sufficiently justified so that he accepts its authenticity. In the development of MEDINFO it was recognized that the task environment, the patient and disease, is highly variable and cannot be completely specified by a rigid, decision tree approach. However, the task can be generally mapped by a structure of decisions and procedures.

To illustrate these principles, we developed a prototype clinical algorithm for pediatric hypertension. The architecture of the system is illustrated in Figure 8. The physician visualizes MEDINFO as a knowledge base of expertise for specialty problem areas. This expertise is accessed through a computer graphics terminal located in the office or clinical site. Each encounter with the system begins with a search of an index which provides access to a variety of clinical algorithms and supporting materials maintained by MEDINFO.

Figure 8 highlights the specific problem of hypertension in children. As an example of a task to which the system applies, assume that a family doctor has been asked to certify a twelve year old boy's fitness to play basketball.

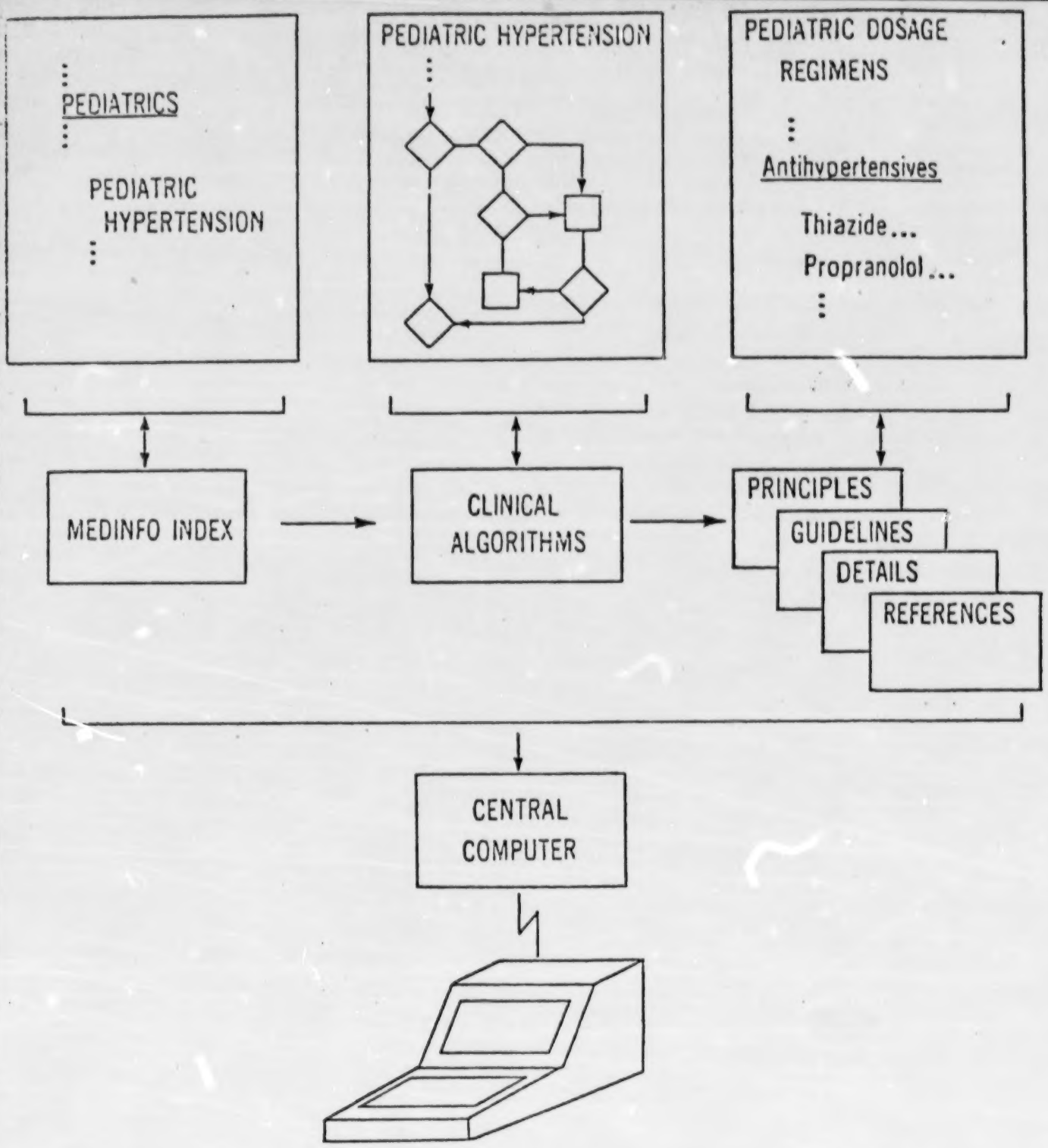


Figure 8. ILLUSTRATION OF THE MEDINFO SYSTEM

While studying data from a physical examination, the physician notices that the boy's blood pressure is 130/89. Three questions should occur to him:

1. Is that value normal?
2. If not, what should be done about it?
3. Should the boy be allowed to play basketball?

These questions may not be answered correctly because the physician fails to recognize the problem or lacks information about it and has insufficient time to look up needed information in traditional sources such as textbooks or journal articles. MEDINFO could provide the family physician with decision support in the form of the transformed expertise of the pediatric cardiologist, pediatric nephrologist, and the clinical pharmacologist.

The system is designed to provide support through a "workspace" that reduces cognitive strain and is tailored to the cognitive model of decision-making. It provides:

1. An explicit planning structure (clinical algorithm) that allows the user to think about his case from beginning to end, from diagnosis to management, and prompts attention to relevant issues that the system knows are important and should not be overlooked.

2. Easily accessible domain knowledge in the form of facts, principles, and alternative solutions which are keyed to the clinical algorithm. This knowledge supplements and reduces reliance upon the user's fallible memory.

3. Means for building a cognitive image of the patient problem which helps the user to keep track of his thoughts as he attempts to reason through implications of the patient data, thereby reducing both the amount of information that must be kept in his own working memory and the need for extensive, high-level, conscious processing. More explicit support of the cognitive image in the form of selective information storage is being planned for the next version of MEDINFO.

Expertise delivered through the workspace takes the form of planning knowledge, domain knowledge, and meta-knowledge. To draw upon this knowledge effectively, the physician must reformulate his problem (this boy with blood pressure 130/89) into a form which has the essential features of a model of

hypertension in children, developed for the system by recognized experts in this field. This reformulation is accomplished while examining layers of knowledge within the workspace.

Figure 9 shows a sample workspace, accessed via the keyword search of the MEDINFO index, displayed on the screen of a graphics terminal. The right side provides planning knowledge as a flow diagram containing key decision and procedures in diagnosing, evaluating, and managing pediatric hypertension. This is the first of several hierarchical layers of procedural knowledge. Each layer helps the physician user organize his thoughts about the patient at one level of specificity of the problem. Portions of each diagram can be expanded or elaborated, level after level, until the user reaches a level of detail consistent with how he has been able to formulate his patient's problem. The upper left-hand area of the workspace is keyed to the planning space on the right and provides the user with entry points to domain knowledge relevant to his current level of thinking.[7] The lower-left hand portion represents the meta-knowledge needed to proceed through the planning structure. (Other forms of meta-knowledge are supported through information about common errors, etc.) Commands for the system have been standardized and permit easy transitions between layers of planning knowledge and ready access to levels of domain knowledge.

The questionable status of the present blood pressure reading might prompt the user to enter at node A: "Document the presence of high blood pressure". Another screen would then appear and offer guidelines and standardized blood pressure curves. The physician could then request these (Figure 11) and would then be able to make a judgment about the specific values for his patient.

---

[7] The separation of the flow diagram structure and text was largely a result of technical limitations. Combining the two would increase comprehensibility and we are trying to implement this for future versions. See Figure 10.

HYPERTENSION IN CHILDREN

a. Document the presence of HBP
b. Is this a HBP emergency? (criteria)
c. Management of Hypertensive Emergency
d. Should patient be hospitalized for evaluation?
e. Does the BP indicate a need for outpatient evaluation?
f. Has borderline HBP been documented at least 3 times?
g. Outpatient evaluation (guidelines)
h. Abnormal findings/diastolic BP extreme
i. Need a consultant for the case?
j. Contact specialist
k. Hospitalize...Inpatient evaluation (guidelines)
l. Is HBP secondary to another disease?
m. Management of secondary Hypertension
n. Is HBP controlled by treatment? (criteria)
o. Monitor BP...Counsel on health care (guidelines)
p. Management of essential hypertension

• ENTER the letter of the node >

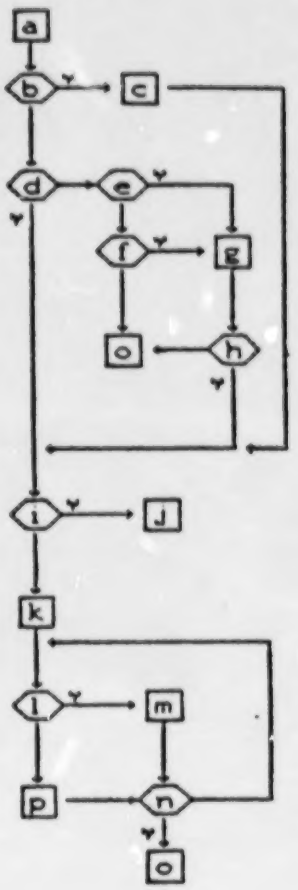
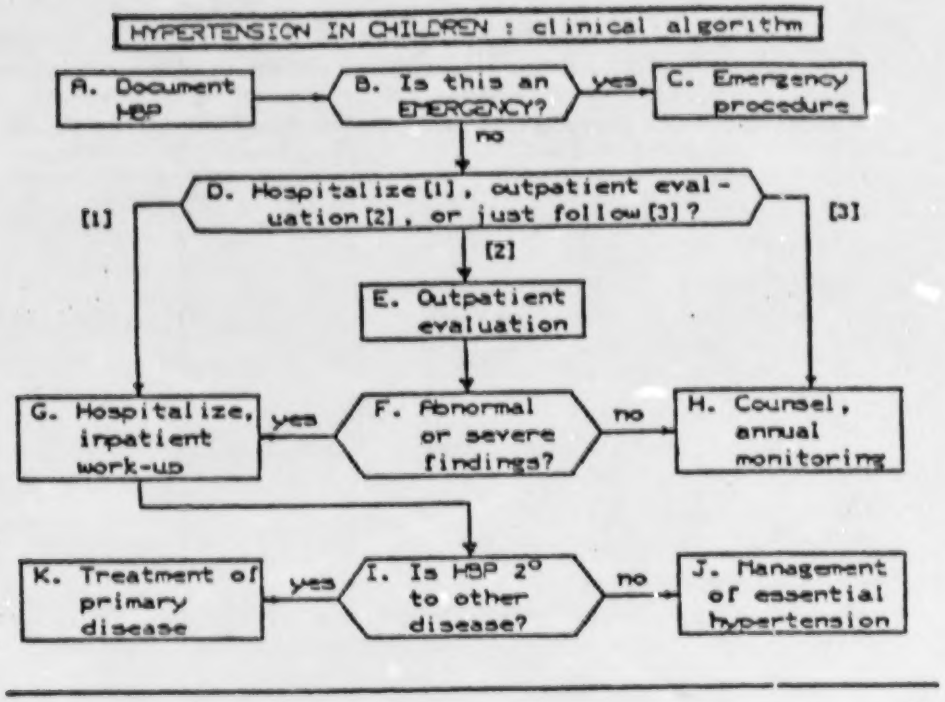


Figure 9 WORKSPACE FOR THE TRANSFER OF PHYSICIAN EXPERTISE

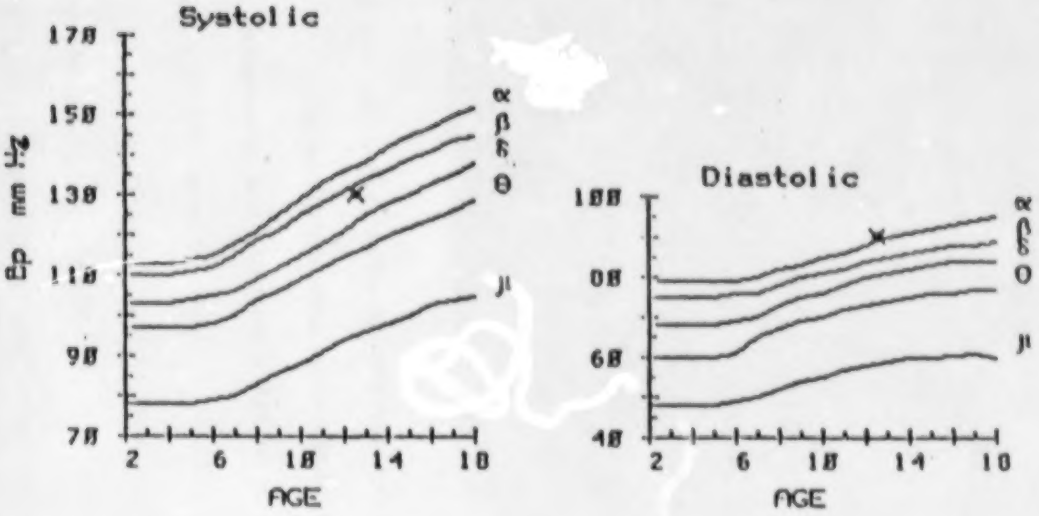
Revised top-level algorithm for pediatric hypertension in MEDINFO



• ENTER the letter of the node >

Figure 10

NORMAL BLOOD PRESSURE TABLES



Percentiles
α → 95th
β → 90th
δ → 75th
θ → 50th
μ → 5th

```
Age?      12.5 ok
Systolic BP?    130 ok
Diastolic BP?    90 ok
Clear plot, start over?
```


Figure 11

Assuming that the physician decides the boy is hypertensive, the clinical algorithm would serve as a logical structure for diagnosing and managing the case, reminding him of questions to ask himself and procedures to consider. The user can enter or exit at any node, and request desired domain knowledge in the form of principles, guidelines, criteria, and detailed information. For example, if information on managing essential hypertension is needed, recommended management practices can be quickly retrieved (Figure 12), which could be supplemented with greater detail. Other information available includes discussions if controversial issues, and principles of pathophysiology, to help the user understand and justify diagnostic and management decisions. It is important to note that the system does not make clinical decisions, which remain the responsibility of the physician. Rather, it supports decision-making and educates the user in task-relevant ways.

Conclusion

We have proposed design objectives and design principles for developing decision support systems in medicine based upon consideration of:

1) the user of such systems as a fallible information processor,
2) the expert in the domain as a guide to what information the user needs to be successful in the decision-making task, and
3) the similarities between novice and expert as a guide to how information should be organized for presentation to the user.

Our model has suggested ways in which a decision support system can augment medical expertise, and has proven to be a feasible basis for the design of a prototype for such a system, but test of its usefulness and effect upon clinical thinking must await further development.

RECOMMENDED MANAGEMENT PRACTICES

- Diastolic BP Range → 90-109 mm Hg
- Age Grouping → 7-12 yrs
- Management Step → I

In this group of patients, the initial antihypertensive drug is usually a thiazide diuretic, as hydrochlorothiazide.

The STARTING DOSE in children is usually → 1 mg/Kg

If a satisfactory therapeutic response is not achieved WITHIN 2 WEEKS the dosage can be increased to → 2mg/Kg

NOTE: Hydrochlorothiazide dosages in excess of 2mg/Kg improve neither diuretic effectiveness nor anti-hypertensive action.

The only ADVERSE DRUG REACTION noted to occur with any regularity in children is "hypokalemia". This is most common during the first or second week of treatment; thus FREQUENT MONITORING of serum electrolytes is mandatory during the early phase of thiazide therapy, and periodically thereafter.

More information is available on this drug.

a. Uses

b. Contraindications

c. Adverse Drug Reactions

d. Drug Interactions

e. Dosage

f. Patient Instructions

g. Detail on drug

- Enter a letter for more information >

Figure 12 KNOWLEDGE FOR TREATING HYPERTENSION IN CHILDREN

4. SUMMARY

This paper has described three instructional projects at the University of Minnesota. They represent products for increasingly sophisticated learners - from beginning to advanced medical students and post-graduate fellows to practicing physicians - and accordingly emphasize different applications of a model of expertise - from strengthening domain knowledge to demonstrating and analyzing the formation of a cognitive image of a case to supporting decision-making by providing information tailored to clinical tasks. Together, they illustrate ways in which a model of expertise may suggest innovative applications to practical instructional problems.

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Appendix A

Sample on-line questionnaire results, year 1, congenital heart disease.

Responses to item 115

At this point, how helpful have you found this program to be ?

Not at all helpful	1	2	3	4	5	Very helpful
	0	0	8	23	16	

There were 47 responses to this item. On the 1 to 5 scale the average response was 4.17.

Responses to item 116

Would you be interested in going through such a program for another topic, if it was available ?

No way	1	2	3	4	5	Without a doubt
	0	0	0	10	37	

There were 47 responses to this item. On the 1 to 5 scale the average response was 4.79.

Responses to item 117

Please rate the difficulty of the questions :

Insultingly easy	1	2	3	4	5	Frustratingly hard
	0	2	32	13	0	

There were 47 responses to this item. On the 1 to 5 scale the average response was 3.23.

Responses to item 118

Do you plan to use the suggested references ?

I won't use any of them	1	2	3	4	5	I will look at almost all
	3	14	19	9	2	

There were 47 responses to this item. On the 1 to 5 scale the average response was 2.85.

Responses to item 119

Do you plan to take the printout with you and use the the comments for review ?

I won't look at any of them	1	2	3	4	5	I'll go over almost all
	3	2	6	11	25	

There were 47 responses to this item. On the 1 to 5 scale the average response was 4.13.

Responses to item 120

Was the presentation of objectives helpful ?

They were a waste of time	1	2	3	4	5	They clarified the topic very much (or were otherwise helpful)
	7	10	19	6	5	

There were 47 responses to this item. On the 1 to 5 scale the average response was 2.83.

Appendix B: Workbook Exercises and Feedback

Um, I would start by taking a little, in respect to birth history I would want to know some specific details in respect to the gestation, whether there were any particular difficulties the mother experienced during the pregnancy, particularly in respect to any unusual medications with the exception of vitamins and iron.

****

1. LIST TWO OR THREE POSSIBLE ABNORMALITIES OR DIFFICULTIES OCCURING DURING PREGNANCY WHICH MIGHT SUGGEST PARTICULAR CARDIAC DIAGNOSES; LIST THE MOST LIKELY CARDIAC DIAGNOSIS OF EACH.

****

And was she aware of any difficulty that the baby had in the newborn nursery with?
(Well the baby was jaundiced she would say to you.)
Okay.
(And that was apparently because the blood types were different she would say to you.)
Okay.
(But that all went okay.)
The baby required no specific treatment as far as exchange transfusions that she's aware of?
(No exchanges.)

For cardiac disease, we would want to know if problems in neonatal period such as cyanosis, tachypnea. Here another unrelated problem, jaundice, was uncovered and carried through to satisfaction of examiner that it was correctly handled and there was no complication.

2. IN THE EVENT THAT CYANOSIS IS DISCOVERED TO BE PRESENT SHORTLY AFTER BIRTH, WHAT DIAGNOSES SHOULD BE IMMEDIATELY CONSIDERED AND WHAT QUESTIONS SHOULD FOLLOW?

EXERCISE ANSWERS

1.

Abnormality or Difficulty	Cardiac Diagnosis
Prematurity	PDA
Old maternal age	Down's Syndrome, VSD
Rubella	PDA

2. A list of considerations would include; Transposition of the great vessels, Truncus Arteriosus, Total Anomolous Pulmonary Venus Connection, Tetrology of Fallot, and Tricuspid Atresia.
Questions which should be subsequently pursued should relate to the severity and course of cyanosis. Other questions about congestive cardiac failure and symptoms in the neonatal period suggesting cardiac disease should be pursued.